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Shear strength estimations and shear designs on RC beams with limited ductility by FL and FIL methods

BM ve BTM yöntemleri ile sınırlı sünekliğe sahip betonarme kirişlerde kesme dayanımı tahmini ve kesme tasarımı

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Abstract

In this study, a fuzzy logic model was constituted by using the Fuzzy Logic (FL) method, which is one of the traditional artificial intelligence (AI) methods, in order to estimate the shear strength of reinforced concrete (RC) beams with limited ductility. In this model, beam width(b_w), beam height(h), characteristic concrete compressive strength(f_{ck}), transverse reinforcement diameter(ϕ_T), the number of arms bearing the shear force of the transverse reinforcement(n) and transverse reinforcement spacing(s) were taken into account as variable parameters. The model developed by using the problem data containing the solutions of shear force strength of 2640 beams with different cross-section properties were tested with 480 beam solutions different from these data. In the tests of the developed *FL* model, maximum percentage error, minimum percentage error, average percentage error and correlation coefficient values were obtained as *3.604, -0.091, 1.514* and $R^2=0.999678$. By applying the fuzzy inverse logic method *(FIL)*, which was recently developed by the author of this study, on the FL model, which is seen to have been developed quite sensitively from the test results, a total of 521 designs were obtained for 15 different RC beams with limited ductility subjected to shear. In order to check the accuracy of these designs, after shear strengths were obtained by conventional computations for these designs, % error and correlation coefficients were computed between the obtained strength values and the shear force values taken into account for the design. The promising results show that the FIL method can be used in the design of RC beams under shear force and even in other scientific studies such as design, optimization and control.

Keywords: Artificial intelligence, Fuzzy logic, Fuzzy inverse logic, Inverse logic, Reinforced concrete beam, Shear design

Öz

Bu çalışmada, sünekliği sınırlı betonarme kirişlerin kesme dayanımını tahmin etmek için geleneksel yapay zekâ yöntemlerinden biri olan Bulanık mantık (BM) yöntemi kullanılarak bir bulanık mantık modeli oluşturulmuştur. Bu modelde kiriş genişliği(b_w), kiriş yüksekliği(h), karakteristik beton basınç dayanımı(f_{ck}), enine donatı çapı($\square_T$), enine donatının kesme kuvvetini taşıyan kol sayısı(n) ve enine donatı aralığı(s) değişken parametreler olarak dikkate alınmıştır. Farklı kesit özelliklerine sahip 2640 kirişin kesme kuvveti dayanımı çözümlerini içeren problem verileri kullanılarak geliştirilen model, bu verilerden farklı olarak 480 kiriş çözümü ile test edilmiştir. Geliştirilen bulanık mantık modelinin testlerinde maksimum yüzde hata, minimum yüzde hata, ortalama yüzde hata ve korelasyon katsayı değerleri 3.604, -0.091, 1.514 ve $R^2=0.999678$ olarak elde edilmiştir. Bu çalışmanın yazarı tarafından yakın zamanda geliştirilen bulanık ters mantık (BTM) yöntemi, test sonuçlarından oldukça hassas bir şekilde geliştirildiği görülen bulanık mantık modeli üzerinde uygulanarak, kesme kuvveti etkisindeki 15 adet sınırlı sünekliğe sahip farklı betonarme kiriş için toplam 521 tasarım elde edilmiştir. Bu tasarımların doğruluğunu kontrol etmek için, bu tasarımlar için geleneksel hesaplamalarla kesme dayanımları elde edildikten sonra, elde edilen dayanım değerleri ile tasarım için dikkate alınan kesme kuvveti değerleri arasında % hata ve korelasyon katsayıları hesaplanmıştır. Elde edilen umut verici sonuçlar, bulanık ters mantık yönteminin kesme kuvveti etkisi altındaki betonarme kirişlerin tasarımında ve diğer bilimsel alanlardaki tasarım, optimizasyon ve kontrol çalışmalarında da kullanılabileceğini göstermiştir.

***Anahtar kelimeler**: Betonarme kiriş, Bulanık mantık, Bulanık ters mantık, Kesme tasarımı, Ters mantık, Yapay zekâ*

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1. Introduction

Today, *AI* has been the subject of many successful applications in the field of civil engineering as well as in many scientific fields. *AI* methods, which process numerical data previously obtained from experiments or collected from various sources with their own algorithms, are widely used today in estimation, evaluation and classification problems in general. *FL* is an *AI* method (Zadeh, 1965, 1973, 1975; Mamdani, 1975, 1976) in which the inferences that people make in the face of various cases related to the knowledge and experience they have acquired are converted into algorithms mathematically and graphically.

Some of the studies carried out recently with *FL* for the estimation of a certain parameter in civil engineering field are about prediction of concrete elements behavior (Naderpour et al., 2019), sensitivity analysis for capacity estimation of *FRP* strengthened circular RC columns (Uzunoğlu & Kap, 2012), prediction of concrete compressive strength in buildings (Tekeli et al., 2014), comparison of critical column buckling load in regression (Mirrashid & Naderpour, 2020), estimation of compressive strength of masonry made of clay bricks and cement mortar (Garzón-Roca et al., 2013), determination of inelastic displacement ratios of degrading *RC* structures (Ozkul et al., 2014), predicting the lateral confinement coefficient for *RC* columns wrapped with carbon fiber reinforced polymer (*CFRP)* (Doran et al., 2015), estimate shear contribution of fiber reinforced polymer (*FRP)* in strengthened *RC* beams (Naderpour & Alavi, 2017), prediction of bond strength of spliced steel bars in concrete (Golafshani et al., 2012), automated serviceability prediction of *NSM* strengthened structure (Ud Darain et al. 2015), prediction of shear strength of RC beams (Amani & Moeini, 2012), downtime estimation of building structures (De Iuliis et al., 2019). Some of the studies in which the FL method is used for evaluation purposes in civil engineering problems are: post-earthquake assessment of buildings damage (Allali et al., 2018), evaluation and monitoring of impact resistance of FRC (Cao et al., 2021), rapid visual earthquake hazard evaluation of existing buildings (Şen, 2010), building earthquake hazard assessment (Şen, 2011), rapid evaluation of earthquake hazard safety of existing buildings (Harirchian & Lahmer, 2020). Finally, as examples of some recent *FL* studies for classification purposes in the field of civil engineering, the studies about computational parameter identification of strongest influence on the shear resistance of RC beams by fiber reinforcement polymer (Cao et al., 2020), real-time strength monitoring for concrete structures (Choi et al., 2018), recognition model for diagnosing cracks in RC structures (Chao & Cheng, 1998), classification of seismic damages in buildings (Elenas et al., 2013), parameters ranking based on influence on dynamical strength of ultra-high performance concrete (Cukaric et al., 2019), identification of multiple cracks on beam (Govardhan et al. 2021), responses of isolated building with MR Dampers (Khoshnoudian & Molavi-Tabrizi, 2012), optimal semi-active structural control (Zabihi-Samani & Ghanooni-Bagha, 2019), selection of slab formwork system (Elbeltagi et al., 2011) , seismic design of RC bridge piers with single-column type (Sung & Su, 2010), *FL* design approach for a singly RC beam (Akintunde , 2021) and etc. are shown. In addition to the studies carried out for these three purposes (estimation, evaluation and classification), design studies are the most important research and study subject in the field of civil engineering as in all engineering fields.

As can be seen from the technical literature, there is almost no design study with *AI* in all scientific fields. Although the word "design" is mentioned in the title of some studies, the content of these studies cannot fully fill the meaning of the word "design" in engineering disciplines. The main reason for this is that the basic computation principles of *AI* methods. Generally, intermediate values can be produced in the range of available data by the traditional *AI* methods and computation directions in these methods are from the input parameter(s) toward the output parameter(s).

On the other hand, because of the input parameters are adjusted for a specific purpose or output in the design studies, the computation directions should be from the output toward the input parameters. Therefore, it cannot be possible to use traditional analytical methods and *AI* methods directly and in general, the trial and error method is used together with these methods in design studies. However, after many trials, only a design can be realized by traditional methods.

In the following parts of this study, after brief information about the *FL* method and computation details of *FIL* methods were presented, shear strength calculation steps for RC beams with limited ductility according to the Turkish Building Code (TS 500, 2000) and Turkish Earthquake Code (TBEC, 2018) provisions were given. By using these codes, necessary data for an FL model aimed to be developed to estimate the shear strength of RC beams with limited ductility was constituted. After the developed *FL* model was tested, designs of 15 different beams subjected to shear force by applying the *1D FIL* method on this *FL* model were performed and finally, obtained designs were checked by conventional shear strength computations. This study is considered to be very important as it is one of the rare studies in which *AI* is applied to design problems in the field of engineering.

2. Fuzzy logic (FL) method and fuzzy inverse logic (FIL) method

2.1. A brief information about fuzzy logic (FL)

The computation processes performed in the FL method can be summarized in 4 steps (See Figure 1). In the first step, the known input and output data of the problem are fuzzified with the help of membership functions. As the membership function, any function suitable for the problem or one of the most known and preferred membership functions such as triangle, trapezoid, sigmoid, step functions, etc. can be used in the fuzzification processes. In fuzzification processes, known net input and net output data are classified into fuzzy sets. In this study, the triangular function is used as a membership function in the fuzzification processes. The second important step of the *FL* method is the constitution of the rule matrix (table). In this step, the rule matrix is constituted with fuzzy inferences corresponding to the combinations of fuzzy sets of fuzzy input parameters. The third step, in which fuzzy outputs are calculated according to the rules in the rule matrix with the *FL* inference engine, is followed by the last step in which the fuzzy outputs are converted into net outputs with the help of the selected defuzzifier method. There are many defuzzifier methods used in *FL* computations. In this study, the "Weighted Average Method" was used as the defuzzifier method. Since many details about FL computations can be obtained from many books and articles in the technical literature, they were not given in this study (Zadeh, 1965, 1973, 1975; Mamdani, 1975, 1976).

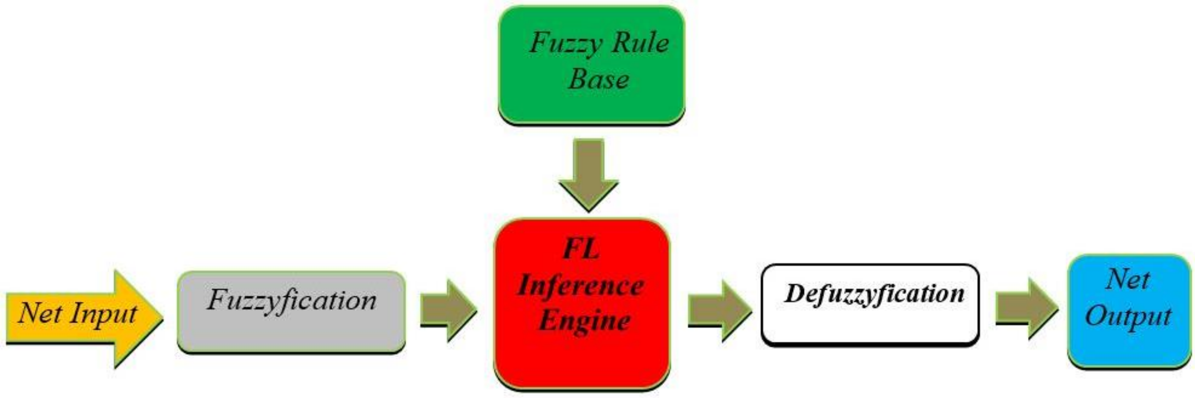

Figure 1. Flowchart of fuzzy logic method

2.2. Fuzzy inverse logic (FIL)

The *FIL* method was developed by the author of this study in a way that is the same as the entire logical infrastructure of the *FL* method, but the computational steps are in the opposite direction of the computational direction in *FL*. As can be seen more clearly from Figure 2, in the FIL method, the values of the input parameters for a targeted(desired) output are tried to be determined. In the development of the *FIL* method, the author of this study inspired by the human's ability to infer backward.same earthquake zone, the current map predicts earthquake parameters specific to each geographical location. The variation of the seismicity elements according to the geographical location also directly affects the structural parameters to be obtained from the earthquake data. With the current map, the concept of the earthquake zone has also been removed. The representation on the current earthquake hazard map is shown in Figure 2.

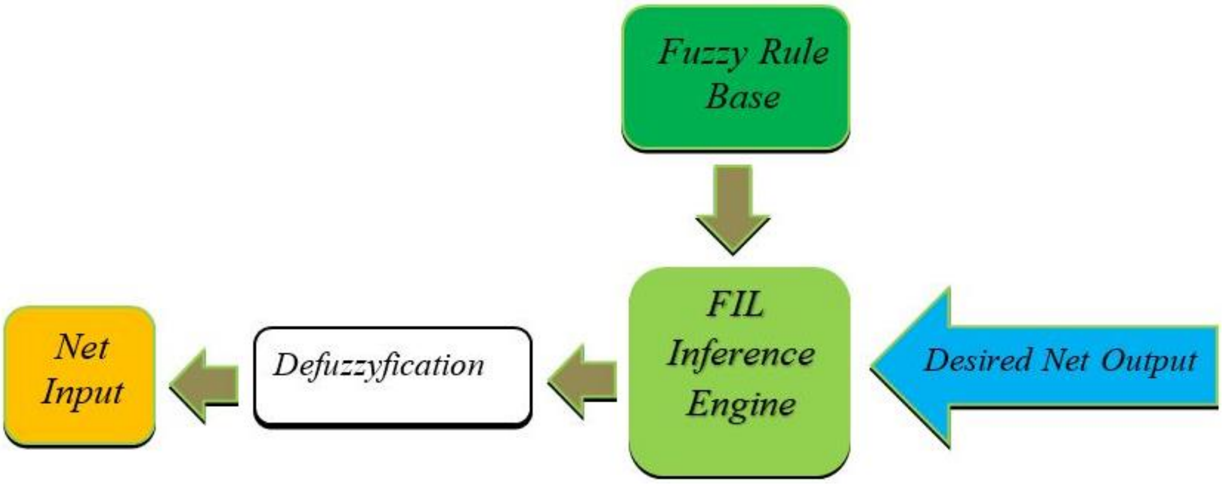

Figure 2. Flowchart of fuzzy inverse logic method

An *FL* model is needed for the *FIL* method to be applied. This model can be developed specifically for the *FIL* method, or it can also be a previously developed *FL* model. The most important point to be emphasized here again is that the *FL* model on which the *FIL* method is applied must be developed very well and/or sensitively and the same defuzzifier method must be used in both *FL* and *FIL* methods. The computations performed in *FIL* are explained in detail step by step below.

Step-1) A highly sensitive FL model is constituted or selected for FIL computations.
Step-2) The targeted (desired) output locations in the output data of the FL model are determined depending on the computation dimension.
Step-3) The fuzzy coordinates (valid fuzzy sets) of the investigated input parameters are computed in each determined location.
Step-4) The net values of the input parameters are computed with the help of the membership functions of the fuzzy sets of the input parameters,
Step-5) Net values of the input parameters are computed by using the inverse of the defuzzification method depending on the computation dimension, and the conditional expressions in the rules.

In *FIL* computations, the number of computation dimensions can be as much as the maximum number of input variables. However, computations performed in dimensions bigger than 1 are more difficult and more complex and the accuracy of the computations decreases as the dimension increases. In other words, the computations in which the easiest, most understandable and most sensitive solutions are produced are the 1-dimensional (*1D*) computations in the *FIL* method. The sensitivity of the selected or constituted *FL* model is very important in the problem where the *FIL* method will be applied. To put it another way, the sensitivity of the *FIL* method depends entirely on the sensitivity of the *FL* method chosen or constituted. If the sensitivity of the *FL* model is very good, the solutions in the *FIL* method will be more sensitive. Because the *FIL* method uses all the data of the selected or constituted *FL* model as it is. In the application of the *FIL* method, the sensitivity of the *FL* model becomes more important as the computation dimension increases. *FIL* computations performed in a dimension bigger than 1, the amount of error increases exponentially as the number of computation dimensions increases (Öztekin, 2021a, 2021b). For this reason, low-dimensional computations are important in terms of the sensitivity of computations performed with the *FIL* method. In addition, *1D FIL* computations generate direct solutions without the need for any additional iterations, but the number of solutions obtained is less than the bigger dimensions. However, it should be noted that the number of solutions obtained by *1D FIL* computations is quite satisfactory. In fact, sometimes the number of solutions produced is so large that it becomes difficult to choose between them. For these reasons, solutions obtained from *1D FIL* computations are often enough. However, if more solutions are still needed, more solutions can be obtained by *FIL* computations bigger than *1D*. But, error amounts in these solutions will be higher. Since the *1D FIL* method is used in this study, the working principle and computation steps of the *1D FIL* method are tried to be given below in detail.

3. 1D Fuzzy inverse logic computations

In each step of the *1D FIL* method, only 1 of the input parameters of the problem is kept as a variable. Other parameters are taken into account as constants. The values of the parameters kept constant may correspond to the value of the fuzzy sets whose memberships correspond to 1 used in the rule base, or it can also be taken as a different value. In other words, keeping a parameter constant may be required by a condition in the problem. If the net value of an input parameter is different from the net values whose membership is 1 in the fuzzy sets of that parameter, this value is fuzzified and added to the fuzzy sets of the relevant parameter. Then, new outputs and new rules are constituted for all combinations of this new fuzzy set with the fuzzy sets of other input parameters, and these rules are added to the rule base of the *FL* model. This operation is not performed if the net value of the constant parameter (even if it results from a condition in the problem) corresponds to the net value whose membership is 1 in any of its fuzzy sets. Considering the value of all other input parameters except the variable parameter, the fuzzy output in the *FL* method consists of 2 fuzzy sets as shown in Figure 3.

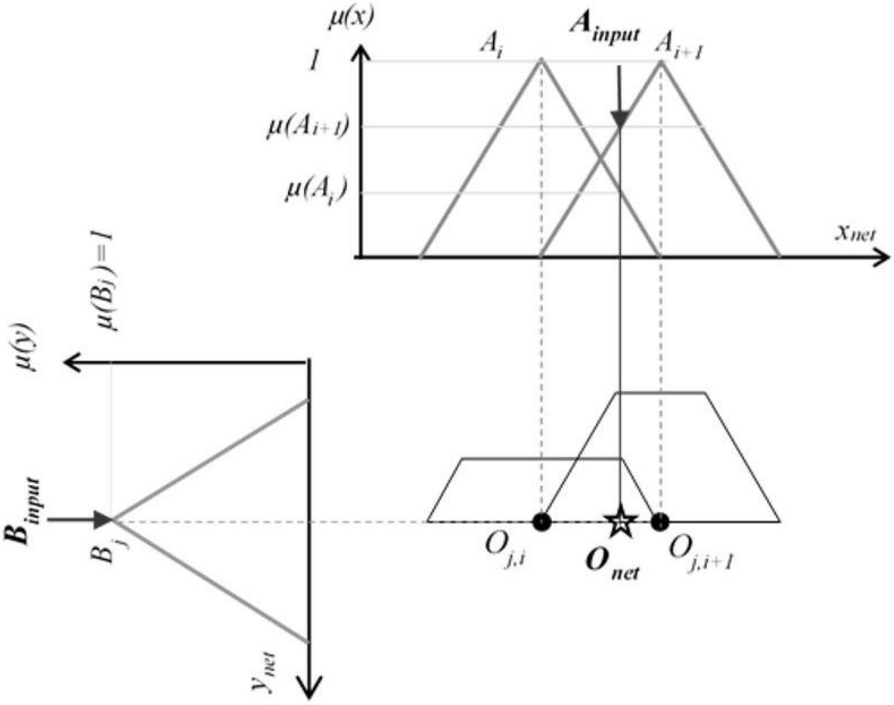

Figure 3. Fuzzy set (B_j) for constant *Y* parameter, adjacent fuzzy sets (A_i, A_{i+1}) for the variable *X* parameter and fuzzy $O_{j,i}$ and $O_{j,i+1}$ outputs

In the solution of a 2-variable problem by the *FL* method shown in Figure 3, when one of the problem variables($Y=B_{input}$) is kept constant, a fuzzy output with 2 fuzzy sets is obtained depending on the value of the other variable ($X=A_{input}$). These two fuzzy sets are consecutive to each other in the fuzzy set space of this variable parameter. The next step in the *FL* method is to convert the fuzzy output to the net value with the help of the selected defuzzifier method. In a problem where the Weighted Average Method is used as a defuzzifier, the net output is computed by Equation 1.

$$O_{net} = \frac{\sum_{i=1}^{n} O_i \cdot \mu_i}{\sum_{i=1}^{n} \mu_i} \quad (1)$$

The relationship between the two consecutive fuzzy sets of A_i and A_{i+1} given by the triangular membership functions of the variable *X* in Figure 3 can be easily written as given in Equation 2. This relationship is valid between the net values corresponding to membership 1 of two consecutive fuzzy sets. In this case, the O_{net} value in Equation 1 can be written more simply as in Equation 3.

$$\mu(A_i) + \mu(A_{i+1}) = 1 \quad (2)$$

$$O_{net} = O_{j,i} \times \mu_{(A_i)} + O_{j,i+1} \times \mu_{(A_{i+1})} \quad (3)$$

In fuzzy models in which membership functions different from the triangular membership function are used, Equation 2 should be revised by another valid relationship. As can be seen from these equations and Figure 3, when the Weighted Average Method is used as defuzziffier, the net output takes place between the net values of $O_{j,i}$ and $O_{j,i+1}$. This may be different when other defuzziffer methods are used and the mathematical equations should be revised according to the used defuzziffer.
If the smaller and bigger of those $O_{j,i}$ and $O_{j,i+1}$ outputs in the above equations are called O_S and O_B, respectively, in the computations made with the *1D FIL* method, it is first investigated whether the targeted or desired O_D output is between these two values(O_S and O_B) as in Equation 4. For this, all fuzzy rules are examined by comparing them for all possible constant values of the other parameters (net values corresponding to membership value 1 of each fuzzy set in their fuzzy space) except the variable parameter.

$$O_s < O_D < O_B \quad (4)$$

For each case that satisfies Equation 4, there is a separate solution. In the next step, fuzzy coordinates are determined for each separate solution. These coordinates are fuzzy sets of the variable parameter in rules that output O_S and O_B in a separate solution. These fuzzy sets are called as valid fuzzy sets for a separate solution in the *FIL* method. In each *1D-FIL* solution, two consecutive sets for the variable parameter and 1 fuzzy set for other constant parameters constitute valid sets for that solution. The net value of a constant parameter is the value corresponding to the membership value 1 of the valid fuzzy set of these parameters. As an example, the B_{input} value of variable X in Figure 4 can be shown. In obtaining the net value of the variable parameter, the reverse of the computation process in the FL method is performed. That is, for the O_{net} output in an *FL* model to be equal to the desired output O_D, the right-hand side of Equation 3 is equalized to O_D as in Equation 5.

$$O_D = O_{j,i}.\mu_{(A_i)} + O_{j,i+1}.\mu_{(A_{i+1})} \quad (5)$$

By using the membership relationship between two consecutive valid fuzzy sets belonging to the variable parameter given in Equation 2, membership values of these two valid sets can be easily computed as in Equations 6 and 7.

$$\mu_{(A_i)} = \frac{O_D - O_{j,i+1}}{O_{j,i} - O_{j,i+1}} \quad (6)$$

$$\mu_{(A_{i+1})} = \frac{O_D - O_{j,i}}{O_{j,i+1} - O_{j,i}} \quad (7)$$

When Equation 6 and Equation 7 are used for each of the two fuzzy consecutive valid fuzzy sets such as A_i and A_{i+1} constituted by a triangular membership function, 2 net inputs are obtained for each separate valid fuzzy set as in Equation 8 and Equation 9. As seen in Figure 4 and given in Equation 10, the sought A input value of variable X is equal to the common net input value of two valid consecutive sets.

$$f(x_i) = \mu_{(A_i)} \rightarrow x_i = \begin{cases} {A_i}^1 \\ {A_i}^2 \end{cases} \quad (8)$$

$$f(x_{i+1}) = \mu_{(A_{i+1})} \rightarrow x_{i+1} = \begin{cases} {A_{i+1}}^1 \\ {A_{i+1}}^2 \end{cases} \quad (9)$$

$$X_{net} = {A_i}^2 = {A_{i+1}}^1 \quad (10)$$

4. Determining of shear strength of rectangular RC beams with limited ductility

In this study, shear strength estimations and designs of rectangular RC beams with limited ductility levels were performed according to two regulations current in Turkey. The first of these regulations is “Requirements for design and construction of RC structures (TS 500-2000) and the second is “Turkish Building Earthquake code (TBDY-2018).

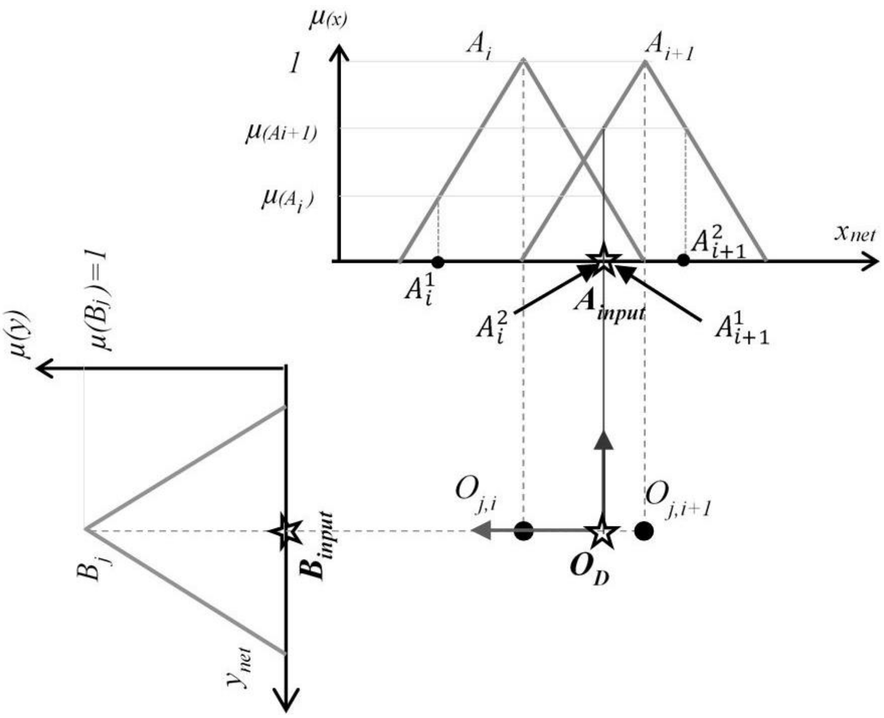

Figure 4. Determination of membership degrees and of net input values in *1D FIL* method.

In a beam with shear reinforcement, it is generally accepted that the shear effect caused by external loads is beared by four different forces emerging inside the beam cross-section, as shown in Figure 5 (Doğangün 2021).

These four internal forces are, the shear force beared by the concrete in the uncracked compression zone of the beam cross-section(V_{cc}), the vertical component of the shear force on the surface of the cracks emerged from the shear effect in the beam cross-section, (V_{ci}), Shear force beared by the longitudinal reinforcement in the tensile zone of the beam *(V_{cd})* and the force beared by the shear reinforcement is ($V_w = \Sigma F_{sw}$).

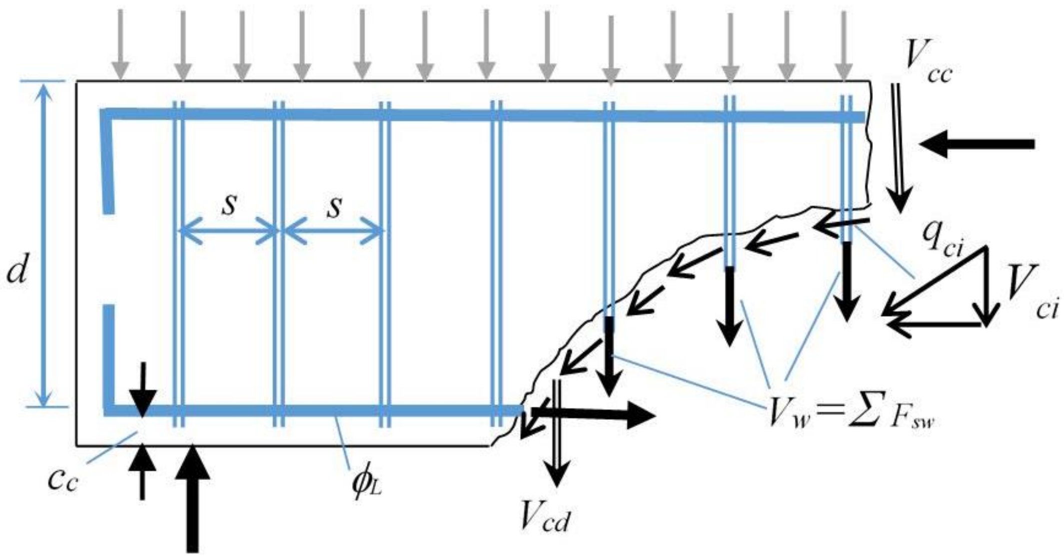

Figure 5. Bearing of shear effect by internal forces emerging inside of the beam cross-section (Doğangün 2021).

The total shear force that the beam can beat can be determined by Equation 11.

$$V_r = V_{cc} + V_{ci} + V_{cd} + V_w \quad (11)$$

In order to facilitate RC calculations and to provide additional safety, by ignoring of vertical component *(V_{ci})* of the friction force occurring in the cracks in the section and the effect of the longitudinal reinforcement in the tension region of the section *(V_{cd})* and the relationship given in Equation 12 is used in general.

$$V_r = V_c + V_w \tag{12}$$

In Equation 12, the shear force beared by the concrete cross-section is shown with the symbol "V_c" and is calculated with the help of Equation 13, Equation 14, Equation 15 and Equation 16 given below.

$$V_c = 0.8 \times V_{cr} \tag{13}$$
$$V_{cr} = 0.65 \times f_{ctd} \times b_w \times d \tag{14}$$
$$f_{ctd} = \frac{f_{ctk}}{\gamma_{mc}} \tag{15}$$
$$f_{ctk} = 0.35 \times \sqrt{fck} \tag{16}$$

The relation given with Equation 14 is the cracking strength under the effect of shear in beams with approximately zero axial force value in the Turkish Building Code [34]. The f_{ctd} calculated in Equation 15 is the tensile strength of the concrete and is calculated by dividing the characteristic concrete tensile strength by the material coefficient. In this study, the material coefficient for concrete is taken as $\gamma_{mc} = 1.5$. Equation 16 is recommended in the Turkish Building Code [34] for the calculation of the characteristic tensile strength of concrete. In Equation 16, f_{ck} is the characteristic concrete compressive strength. In addition to the equations given above, in the Turkish Building Code [34], the requirement given in Equation 17 for the shear force acting on the beam must be met in order to prevent the crushing of the concrete due to high principal compressive stresses. If this requirement cannot be met, the cross-section dimensions should be increased.

$$V \leq 0.85 \times b_w \times d \times \sqrt{f_{ck}} \tag{17}$$

The parameter shown by the symbol *d* in Equation 17 is the effective height of the beam and is obtained by subtracting the concrete cover thickness from the section height. The part of the shear force beared by the shear reinforcement, V_w, is calculated with the equation given in Equation 18.

$$V_w = \frac{A_{sw} \times f_{ywd} \times d}{s} \tag{18}$$

A_{sw} in Equation 18 is the area of shear reinforcement. Since the area of the shear reinforcement varies depending on the number of stirrup arms, the number of stirrup arms must be taken into account in the calculations. Accordingly, the area to be used in the shear strength calculations of a stirrup with ϕ_w cross-section diameter with *n* number of arms can be calculated with Equation 19. The *s* and f_{ywd} parameters in Equation 18 are the distance between stirrups and the yield strength of the shear reinforcement respectively. The f_{ywd} parameter is calculated by dividing of characteristic yield strength of the shear reinforcement by the material coefficient ($\gamma_{ms} = 1.15$).

$$A_{sw} = n \times \frac{\pi \times \emptyset_w^2}{4} \tag{19}$$

5. Development of an FL model to estimate the shear strength of rectangular RC beams

In this study, after an *FL* model was developed for the estimation of the shear strength of rectangular RC beams with limited ductility, this model was used to perform the designs of different beams under different shear forces by using the *1D FIL* method. For this purpose, beam width (b_w), beam height *(h)*, characteristic concrete strength (f_{ck}), transverse reinforcement diameter (ϕ_T), number of stirrup arms (*n*) and stirrup spacing (*s*) were taken into account as variable parameters. In the calculations, the net concrete cover, the longitudinal reinforcement diameter and the characteristic yield strength of the transverse reinforcement are kept constant as 25 mm, 14mm and 420 MPa respectively. In the constitution of the *FL* model; 3, 4, 2, 2, 4 and 11 fuzzy sets were defined for beam width (b_w), beam height *(h)*, characteristic concrete compressive strength (f_{ck}), transverse reinforcement diameter (ϕ_T), number of stirrup arms (*n*) and stirrup spacing(*s*) respectively. These fuzzy sets are given in Table 1 in detail.

The fuzzy sets of the input parameters of the problem in this study were constituted by using triangular membership functions. These constituted fuzzy sets are shown in Figure 6, Figure 7, Figure 8, Figure 9, Figure 10 and Figure 11 for *b*, *h*, f_{ck}, ϕ_T, *n* and *s*, respectively. For all combinations of all these fuzzy sets belonging to the input parameters of the problem, 2640 conventional shear strength computations were made. By using 1673 different results obtained from these computations, fuzzy sets belonging to the output parameter V_r were constituted. Since showing 1673 fuzzy sets with triangular membership functions could not be possible in this study, they could not be presented. 2640 rules were constituted for 2640 input parameter combinations. In these constituted rules, the term "*AND*" was used as the condition term. The general expression used to constitute the rule in this study is given in Equation 20. In addition to all these, the “Weighted Average Method”, whose mathematical expression is given by Equation 1, was used as the defuzzifier method in the developed *FL* model.

$$if\ b = \{b\}_i\ and\ h = \{h\}_j\ and\ f_{ck} = \{f_{ck}\}_k\ and\ \emptyset_T = \{\emptyset_T\}_n\ and\ n = \{n\}_p\ and\ s = \{s\}_r\ then\ V_r = \{V_r\}_s \quad (20)$$

Table 1. Fuzzy sets used in the development of FL model

Input Parameters	Fuzzy Sets
b_w (mm)	200, 300, 400
h (mm)	300, 400, 500, 600
f_{ck} (MPa)	20, 25, 30, 40, 50
ϕ_T (mm)	8, 10
n	2, 4
s	50, 75, 100,125 150,175, 200,225, 250,275, 300

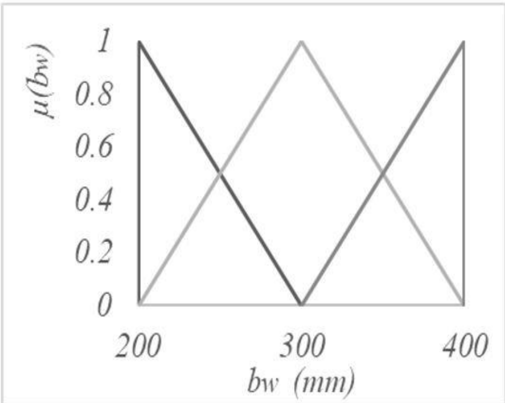

Figure 6. Fuzzy sets constituted for beam width (b_w)

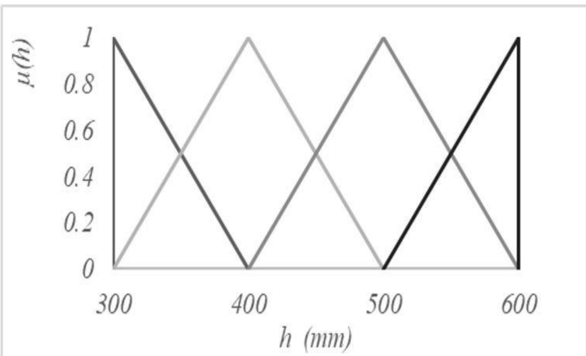

Figure 7. Fuzzy sets constituted for beam height (*h*)

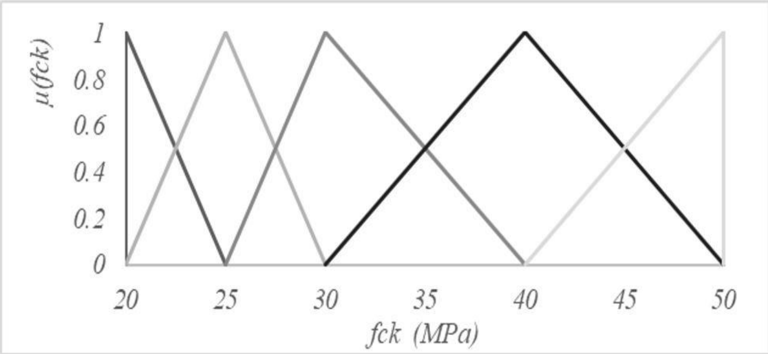

Figure 8. Fuzzy sets constituted for characteristic concrete compressive strength(f_{ck})

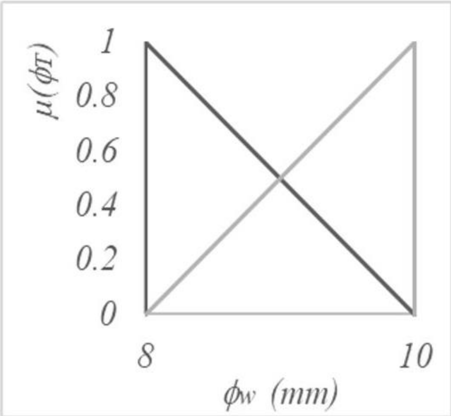

Figure 9. Fuzzy sets constituted for transverse reinforcement diameter (ϕ_T)

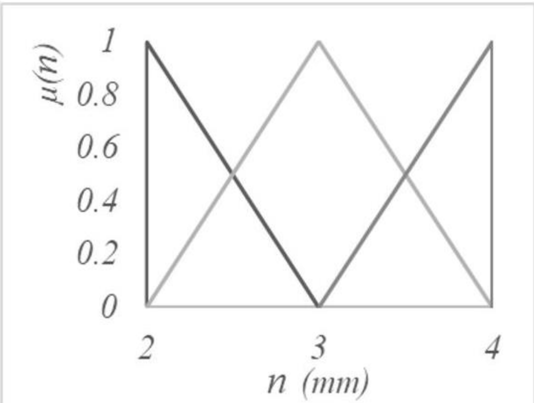

Figure 10. Fuzzy sets constituted for transverse reinforcement arm number (n)

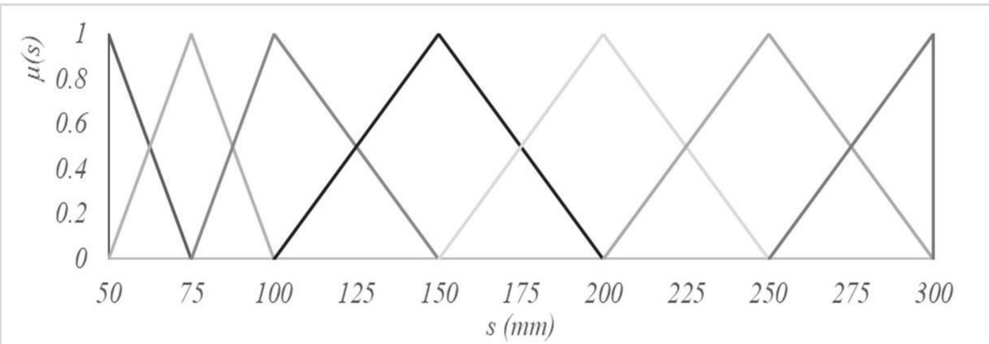

Figure 11. Fuzzy sets constituted for transverse reinforcement spacing (s)

6. Validation of the FL model

In this study, 480 beam sections different from 2640 different RC beam sections used in the constitution of the *FL* model were used to determine whether the *FL* model constituted for the estimation of the shear strength of RC beams with limited ductility produces correct results and to understand the sensitivity of the results produced. It is a common view in the literature that in validation processes, the number of tests should be at least 10% of the number of samples that constitute the model. In this study, the number of tests is more than 18% of the 2640 samples that constitute the data of the *FL* model. This shows that the number of tests used in the validation processes in this study is sufficient.

In the test computations, completely different values were used for the b_w, h, f_{ck} and s input parameters from the values used in the constitution of the fuzzy model and given in Table 1. The same values in Table 1 were used for the diameter of transverse reinforcement ($\square_T$), and the values given in Table 2 for the number of transverse reinforcement arms *(n)* were used.

After the shear strengths of 480 beam sections, which are different from the beam sections used in the constitution of the *FL* model, were estimated with the developed *FL* model, these outputs were compared with the conventionally computed shear strengths for the same beam sections to determine the accuracy and sensitivity of the *FL* outputs. For comparisons, the formula of % error given by Equation 21 was used.

Table 2. Input parameter values used in testing phase of the FL model

Input Parameters	Fuzzy Sets
b_w *(mm)*	*250, 350*
h (mm)	*350, 450, 550, 650, 750*
f_{ck} *(MPa)*	*23, 28, 35, 45*
ϕ_T *(mm)*	*8, 10*
n	*2, 3, 4*
s	*60, 90, 125, 225, 275*

$$\%\ error = \frac{Vr^{FL} - Vr^{Conventionally}}{Vr^{Conventionally}} \times 100 \qquad (21)$$

As a result of the error computations performed with the help of Equation 21, it was determined that the *FL* model constituted in this study could estimate the shear strength of RC beams with a maximum % 3.452 error and minimum % -1.046 error. When these error amounts and the assumptions made in the RC calculations are considered together, it is understood that the FL estimations are quite successful. In addition to error computations, statistical correlation computations between these two results were also performed in order to demonstrate the agreement between conventional results and *FL* estimations. As a result of the statistical correlation computations performed, the correlation coefficient was determined as $R^2=0.999476$ in the distribution seen in Figure 12. As a result, it has been statistically demonstrated that the estimations obtained by the FL method are in good agreement with the conventional computation results.

7. Designs of rectangular RC beams subjected shear forces by FIL method

In order to perform designs of RC beams with limited ductility, the *FL* model constituted as above to estimate the shear strength of these beams and the data of this model were used in the *FIL* method in this study. In order to demonstrate the effectiveness of the *FIL* method, 15 different RC beam design problems are discussed. In Table 3, the values known or required to be taken before the design for the parameters related to these problems and the shear strength values targeted (desired shear strength) in the designs are given together. Targeted (desired) shear strength values were chosen as randomly and as different from each other in such a way that they remain within the value space of the output parameter of the *FL* model. The values shown with the question mark in Table 3 represent the values investigated in the designs for the relevant input parameter or design parameter. Other numerical data show the values of the design parameters that must be taken as mandatory and are limited by factors such as architectural, constructive, etc. before the design. In order to test whether the *FIL* method will produce sensitive results in as many different situations as possible, 15 different beam design problems that are subject to shear were considered in this study.

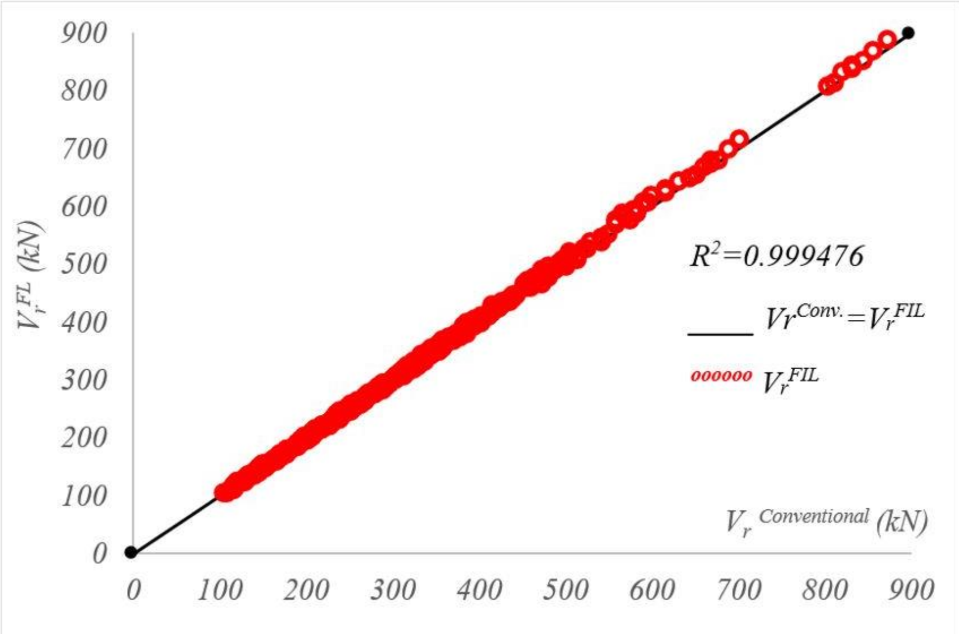

Figure 12. Correlation between FL estimations and conventional computation results

Table 3. Rectangular RC beam problems to be designed using the 1D FIL method

Problem ID	b_w	h	f_{ck}	ϕ_T	n	s	V_r (kN)
1	?	?	?	?	?	?	999.9
2	?	550	?	?	?	?	1222
3	?	?	33	?	?	?	515.5
4	288	555	?	?	?	?	700.7
5	275	412	28	?	?	?	450.0
6	?	600	25	?	?	?	355.9
7	?	?	?	10	2	?	643.2
8	?	?	?	8	4	130	337.5
9	366	495	41	?	3	?	867.6
10	220	350	22	?	2	255	100.8
11	200	300	20	?	?	177	123.4
12	?	?	?	10	?	?	1323.1
13	?	?	?	8	2	300	70.0
14	?	?	50	?	?	70	1100
15	205	302	?	10	2	280	90

In this study, three different codes were written in visual basic coding language for the FL method, FIL method and conventional shear strength computations. The data prepared for use in the FL method with conventional Shear strength computations were used directly in the program written for the FIL method without making any changes at this data.

8. Findings and evaluations

After the designs of 15 different RC beams in Table 3 were determined by the *FIL* method, the maximum shear strengths (V_r) that these designs could bear were determined by conventional RC beam computations to check the accuracy and the sensitivity of these designs. In addition to these, max, min, mean, absolute max and absolute min percentage error computations were made with the help of Equation 21 between the targeted shear strengths and the strengths determined by conventional RC beam computations. All these values for each problem were given in Table 4 together with the number of solutions.

As can be seen from Table 4, the maximum absolute error value determined in a total of 521 designs in 15 different problems is 5.523%. This error value is an acceptable and reasonable error considering the maximum error value of % error 3.452 in the *FL* model and the assumptions taken into account in the RC calculations. The biggest standard deviations in Table 4 were obtained as 11.28 kN, 12.24 kN, 11.23 kN and 15.75 kN, in problems 1, 2, 9 and 12 respectively, where the V_d value is relatively bigger. The largest number of designs were obtained in the 1st, 3rd and 6th problems as 122, 129 and 61 respectively. Obtaining a large number of designs in such problems depends on the number and the attributes of the data in the *FL* model and the number of variable parameters investigated. In general, as the number of variable parameters whose values are investigated increases, the number of designs also increases. In this case, while it is expected that the number of designs obtained in Problem 1 will be greater than that in Problem 3, the highest number of designs from this study was obtained in Problem 3. The reason for this is related to the distribution of the data used in the *FL* model. In other words, this is an indication that the number of outputs close to 515.5 kN in the *FL* model is more than the number of outputs close to 999.9 kN.

Table 4. The mean, standard deviation of V_r values of *1D FIL* designs and percentage errors between V_r and V_d values in each problem

Problem ID	*Design Numbers*	V_d *(kN)*	V_r *(kN)*		*% Error*			*% absolute error*	
			Mean	*Std. Dev.*	*Max*	*Min*	*Mean*	*Maximum*	*Mean*
1	122	999.9	992.27	11.28	0.025	-3.538	-0.763	3.538	0.764
2	44	1222.0	1213.43	12.24	1.197	-4.172	-0.701	4.172	0.793
3	129	515.5	513.16	4.49	0.192	-3.707	-0.453	3.707	0.516
4	35	*700.7*	699.76	7.784	0.717	-2.972	-0.134	2.972	0.799
5	9	*450.0*	435.75	4.105	-2.407	-5.523	-3.168	5.523	3.168
6	61	*355.9*	354.98	1.241	0.099	-1.231	-0.258	1.231	0.272
7	39	*643.2*	635.44	9.351	0.137	-3.459	-1.206	3.458	1.246
8	21	*337.5*	336.18	0.208	-0.287	-0.595	-0.392	0.595	0.392
9	2	*867.6*	883.97	11.23	2.272	1.501	1.886	2.272	1.886
10	1	*100.8*	97.59	-3.184	-3.184	-3.184	-3.184	3.184	3.184
11	2	*123.4*	123.29	0.065	-0.034	-0.139	-0.086	0.139	0.086
12	44	*1323.1*	1314.85	15.75	2.115	-3.269	-0.623	3.270	0.792
13	7	*70.0*	69.44	0.23	-0.347	-1.233	-0.799	1.233	0.799
14	4	1100	1069.34	2.46	-2.451	-3.077	-2.787	3.077	2.787
15	1	90	87.291	0	-3.010	-3.010	-3.010	3.010	3.010

All of the designs obtained for each problem are given in Table 5-19, respectively. As can be seen in these tables, the number of stirrup arms, which should be an integer in practice, was obtained as a real number in some designs by *1D-FIL* computations. In this study, the results are given directly in the tables without any rounding. Controls made with conventional RC computations were performed with these real numbers. In practice, the values of parameters such as the number of stirrups and the number of reinforcements are used by rounding them up. The same is true for classical designs. In fact, rounding operations need to be done in a way that increases the security of the design. For example, for the stirrup spacing, the rounding must be done downwards for the safety of the design. Rounding also causes the error amounts to vary. Considering the smallness of the errors (error ≤~5.523%) in all designs and the assumptions and approaches in RC calculations, all designs become more reliable without losing their applicability by rounding the values of the design parameters given in Table 5-19 to a practically usable number. It should be noted here again that these results are the design results obtained by the *1D FIL* method. Realization of many more designs different from these is possible with *2D, 3D…, n(D) FIL* computations.

The bold values of the design parameters given in Table 5-19 show the parameter considered as a variable for the relevant design in the *1D FIL* method. The values given in italics in the last column of each design show the shear strengths obtained by conventional strength computations of the designs determined by *1D FIL*.

Table 5. Beam designs under 999.9 kN shear force by the *1D FIL* method for Problem-1

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
1	200	**458.052**	20	10	4	50	999.879	62	400	500	30	10	**3.342**	50	999.937
2	200	**455.836**	25	10	4	50	999.854	63	400	500	30	10	4	**62.332**	964.800
3	200	**453.871**	30	10	4	50	999.877	64	400	**598.831**	30	10	4	75	999.871
4	200	**450.408**	40	10	4	50	999.867	65	400	500	40	**8.977**	4	50	989.753
5	200	**447.426**	50	10	4	50	999.910	66	400	500	40	10	**3.270**	50	999.872
6	200	500	20	**9.463**	4	50	991.944	67	400	500	40	10	4	**63.677**	965.828
7	300	600	30	**8.288**	4	50	993.761	68	400	**586.3909**	40	10	4	75	999.921
8	300	600	30	10	**2.776**	50	999.890	69	400	**591.8874**	50	8	4	50	999.914
9	300	600	30	10	4	**72.950**	988.878	70	400	500	50	**8.888**	4	50	989.905
10	**394.340**	600	30	10	4	75	999.872	71	400	500	50	10	**3.207**	50	999.866
11	300	600	40	**8.212**	4	50	995.145	72	400	500	50	10	4	**64.862**	967.353
12	300	600	40	10	**2.722**	50	999.899	73	300	**445.719**	25	10	4	50	999.902
13	200	500	20	10	**3.616**	50	999.891	74	300	**442.903**	30	10	4	50	999.892
14	200	500	20	10	4	**57.194**	968.497	75	300	**438.020**	40	10	4	50	999.927
15	200	500	25	**9.431**	4	50	991.634	76	300	**433.777**	50	10	4	50	999.861
16	200	500	25	10	**3.594**	50	999.858	77	300	500	20	**9.330**	4	50	990.935
17	200	500	25	10	4	**57.613**	967.683	78	300	500	20	10	**3.522**	50	999.943
18	200	500	30	**9.403**	4	50	991.406	79	300	500	20	10	4	**58.964**	965.769
19	200	500	30	10	**3.574**	50	999.862	80	300	500	25	**9.283**	4	50	990.620
20	200	500	30	10	4	**57.991**	967.039	81	300	500	25	10	**3.488**	50	999.944
21	200	500	40	**9.353**	4	50	991.020	82	300	500	25	10	4	**59.592**	965.177
22	200	500	40	10	**3.538**	50	999.879	83	300	500	30	**9.241**	4	50	990.361
23	200	500	40	10	4	**58.662**	966.097	84	300	500	30	10	**3.458**	50	999.900
24	200	500	50	**9.308**	4	50	990.733	85	300	500	30	10	4	**60.163**	964.765
25	200	500	50	10	**3.506**	50	999.876	86	300	500	40	**9.165**	4	50	990.060
26	200	500	50	10	4	**59.254**	965.441	87	300	500	40	10	**3.404**	50	999.926
27	200	600	20	**8.510**	4	50	990.467	88	300	500	40	10	4	**61.169**	964.522
28	200	600	20	10	**2.934**	50	999.899	89	300	500	50	**9.098**	4	50	989.848
29	200	600	20	10	4	**69.980**	975.430	90	300	500	50	10	**3.357**	50	999.871
30	200	600	25	**8.478**	4	50	990.829	91	300	500	50	10	4	**62.058**	964.665
31	200	600	25	10	**2.912**	50	999.901	92	300	600	20	**8.377**	4	50	992.285
32	200	600	25	10	4	**70.397**	977.159	93	300	600	20	10	**2.840**	50	999.876
33	200	600	30	**8.450**	4	50	991.208	94	300	600	20	10	4	**71.755**	983.079
34	200	600	30	10	**2.892**	50	999.908	95	300	600	25	**8.330**	4	50	993.011
35	200	600	30	10	4	**70.777**	978.742	96	300	600	25	10	**2.806**	50	999.897
36	200	600	40	**8.400**	4	50	991.930	97	300	600	25	10	4	**72.382**	986.074
37	200	600	40	10	**2.856**	50	999.881	98	400	**575.8676**	50	10	4	75	999.935
38	200	600	40	10	4	**71.450**	981.688	99	400	600	20	**8.244**	4	50	994.544
39	200	600	50	**8.356**	4	50	992.650	100	400	600	20	10	**2.745**	50	999.916
40	200	600	50	10	**2.824**	50	999.889	101	400	600	20	10	4	**73.530**	991.820
41	200	600	50	10	4	**72.042**	984.438	102	400	600	25	**8.182**	4	50	995.809
42	300	**448.881**	20	10	4	50	999.915	103	400	600	25	10	**2.701**	50	999.912
43	300	600	40	10	4	**73.957**	994.133	104	400	600	25	10	4	**74.362**	996.375
44	**341.589**	600	40	10	4	75	999.907	105	400	600	**29.192**	10	4	75	999.961
45	**369.375**	600	50	8	4	50	999.899	106	400	600	30	**8.125**	4	50	996.979
46	300	600	50	**8.146**	4	50	996.512	107	400	600	30	**9.986**	4	75	999.645
47	300	600	50	10	**2.675**	50	999.861	108	400	600	30	10	**2.660**	50	999.871
48	300	600	50	10	4	**74.848**	998.998	109	400	600	30	10	**3.990**	75	999.871
49	**305.439**	600	50	10	4	75	999.865	110	400	600	30	10	4	**75.24**6	999.180
50	400	**440.088**	20	10	4	50	999.907	111	400	600	**42.759**	8	4	50	1000.152
51	400	**436.066**	25	10	4	50	999.902	112	400	600	40	**8.024**	4	50	999.322
52	400	**432.5**	30	10	4	50	999.897	113	400	600	40	**9.836**	4	75	997.425
53	400	**426.326**	40	10	4	50	999.893	114	400	600	40	10	**2.589**	50	999.917
54	400	**421.039**	50	10	4	50	999.870	115	400	600	40	10	**3.883**	75	999.917
55	400	500	20	**9.197**	4	50	990.179	116	400	600	40	10	4	**77.929**	992.836
56	400	500	20	10	**3.427**	50	999.896	117	400	600	50	8	**3.929**	50	999.912
57	400	500	20	10	4	**60.741**	964.548	118	400	600	50	8	4	**51.341**	993.135
58	400	500	25	**9.135**	4	50	989.980	119	400	600	50	**9.703**	4	75	995.747
59	400	500	25	10	**3.383**	50	999.929	120	400	600	50	10	**2.525**	50	999.907
60	400	500	25	10	4	**61.576**	964.549	121	400	600	50	10	**3.788**	75	999.933
61	400	500	30	**9.078**	4	50	989.885	122	400	600	50	10	4	**80.295**	988.840

Table 6. Beam designs under 1222 kN shear force by the *1D FIL* method for Problem-2

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
1	**257.240**	550	20	10	4	50	1236.630	23	200	550	50	10	4	**52.001**	1208.034
2	200	550	**24.365**	10	4	50	1226.571	24	300	550	20	**9.874**	4	50	1219.536
3	200	550	25	**9.975**	4	50	1221.673	25	300	550	20	10	**3.910**	50	1222.146
4	200	550	25	10	**3.982**	50	1222.224	26	300	550	20	10	4	**51.695**	1210.205
5	200	550	25	10	4	**50.330**	1219.708	27	300	550	25	**9.820**	4	50	1217.083

Table 6. Continuing

6	200	550	30	**9.938**	4	50	1218.891	28	300	550	25	10	**3.871**	50	1220.682
7	200	550	30	10	**3.955**	50	1220.246	29	300	550	25	10	4	**52.410**	1204.569
8	200	550	30	10	4	**50.837**	1214.040	30	300	550	30	**9.784**	4	50	1217.649
9	200	550	40	**9.906**	4	50	1222.098	31	300	550	30	10	**3.845**	50	1221.906
10	300	550	30	10	4	**52.890**	1203.314	32	400	550	20	10	4	**53.437**	1201.012
11	300	550	40	**9.709**	4	50	1216.459	33	400	550	25	**9.676**	4	50	1215.461
12	300	550	40	10	**3.792**	50	1222.110	34	400	550	25	10	**3.768**	50	1221.482
13	300	550	40	10	4	**53.894**	1198.443	35	400	550	25	10	4	**54.341**	1195.877
14	300	550	50	**9.646**	4	50	1216.295	36	400	550	30	**9.597**	4	50	1209.710
15	300	550	50	10	**3.748**	50	1223.147	37	400	550	30	10	**3.711**	50	1216.484
16	300	550	50	10	4	**54.736**	1195.608	38	400	550	30	10	4	**55.429**	1186.582
17	400	550	20	**9.745**	4	50	1217.880	39	400	550	40	**9.526**	4	50	1214.843
18	400	550	20	10	**3.818**	50	1222.848	40	400	550	40	10	**3.662**	50	1223.020
19	200	550	40	10	**3.933**	50	1224.107	41	400	550	40	10	4	**56.425**	1188.908
20	200	550	40	10	4	**51.260**	1215.024	42	400	550	50	**9.370**	4	50	1199.256
21	200	550	50	**9.850**	4	50	1218.611	43	400	550	50	10	**3.547**	50	1207.940
22	200	550	50	10	**3.893**	50	1221.742	44	400	550	50	10	4	**58.480**	1171.017

Table 7. Beam designs under 515.5 kN shear force by the *1D FIL* method for Problem-3

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
1	200	**360.608**	33	8	4	50	515.546	50	300	**572.142**	33	10	2	75	516.364
2	200	300	33	**8.926**	4	50	509.730	51	300	500	33	10	**2.398**	75	515.864
3	200	300	33	10	**3.237**	50	515.033	52	300	500	33	10	**3.196**	100	515.591
4	200	300	33	10	4	**64.293**	496.390	53	300	500	33	10	**3.992**	125	515.291
5	200	**350.965**	33	10	4	75	515.731	54	300	500	33	10	4	**125.310**	515.123
6	200	400	33	8	**3.520**	50	515.502	55	300	**572.142**	33	10	4	150	516.364
7	200	400	33	8	4	**59.018**	498.107	56	300	600	33	8	2	**52.372**	509.686
8	200	400	33	**9.159**	4	75	510.483	57	300	600	33	**9.646**	2	75	514.120
9	200	**442.511**	33	10	2	50	515.364	58	300	600	33	8	**2.912**	75	516.317
10	200	400	33	10	**2.266**	50	515.317	59	300	600	33	8	**3.873**	100	515.232
11	200	400	33	10	**3.403**	75	515.848	60	300	600	33	8	4	**103.954**	512.673
12	200	400	33	10	4	**89.973**	506.437	61	300	600	33	**8.762**	4	125	510.995
13	200	**442.511**	33	10	4	100	515.364	62	300	600	33	**9.646**	4	150	514.120
14	200	500	33	**9.212**	2	50	510.671	63	300	600	33	10	2	**81.370**	510.084
15	200	500	33	8	**2.672**	50	515.375	64	300	600	33	10	**2.491**	100	515.427
16	200	500	33	8	4	**74.818**	515.600	65	300	600	33	10	**3.116**	125	515.655
17	**204.959**	500	33	8	4	75	516.093	66	300	600	33	10	**3.747**	150	516.490
18	200	**501.471**	33	8	4	75	516.149	67	300	600	33	10	4	**161.146**	513.977
19	200	500	33	**8.013**	4	75	515.963	68	**384.985**	600	33	10	4	175	515.577
20	200	500	33	**9.212**	4	100	510.671	69	400	**335.046**	33	8	4	50	515.572
21	200	500	33	10	2	**60.534**	497.895	70	400	300	33	**8.578**	4	50	510.357
22	200	500	33	10	**2.577**	75	515.201	71	400	300	33	10	**2.991**	50	514.681
23	200	500	33	10	**3.438**	100	515.526	72	400	300	33	10	4	**68.869**	501.762
24	200	500	33	10	4	**117.453**	511.253	73	400	**327.126**	33	10	4	75	515.685
25	**297.335**	500	33	10	4	125	515.312	74	400	400	33	8	**3.143**	50	515.858
26	200	**530.312**	33	10	4	125	516.289	75	400	400	33	8	4	**66.059**	500.548
27	**267.171**	600	33	8	2	50	515.499	76	400	**449.743**	33	8	4	75	515.411
28	200	600	33	**8.234**	2	50	513.436	77	400	400	33	**8.649**	4	75	511.428
29	200	600	33	8	**2.130**	50	516.096	78	400	**404.001**	33	10	2	50	516.274
30	200	600	33	8	**3.194**	75	515.833	79	400	400	33	10	**2.028**	50	516.255
31	200	600	33	8	4	**95.116**	510.394	80	400	400	33	10	**3.040**	75	515.981
32	**267.171**	600	33	8	4	100	515.499	81	400	400	33	10	4	**98.961**	514.881
33	200	600	33	**8.234**	4	100	513.436	82	400	**404.001**	33	10	4	100	516.274
34	200	600	33	**9.192**	4	125	511.329	83	400	**472.561**	33	10	4	125	515.250
35	200	600	33	10	2	**73.711**	512.070	84	400	**549.591**	33	8	2	50	516.275
36	**229.060**	600	33	10	2	75	515.908	85	400	500	33	**8.537**	2	50	512.263
37	200	600	33	10	**2.052**	75	515.633	86	400	500	33	8	**2.297**	50	516.170
38	200	600	33	10	**2.734**	100	515.351	87	400	500	33	8	**3.436**	75	515.119
39	200	600	33	10	**3.424**	125	516.220	88	400	500	33	8	4	**88.998**	507.791
40	200	600	33	10	4	**146.738**	514.093	89	400	**549.591**	33	8	4	100	516.275
41	**229.060**	600	33	10	4	150	515.908	90	400	500	33	**8.537**	4	100	512.263
42	300	**347.164**	33	8	4	50	515.338	91	400	500	33	**9.560**	4	125	512.403
43	300	300	33	**8.754**	4	50	510.135	92	400	500	33	10	2	**69.588**	505.264
44	300	300	33	10	**3.118**	50	515.442	93	400	**536.193**	33	10	2	75	515.795
45	300	300	33	10	4	**66.523**	498.940	94	400	500	33	10	**2.214**	75	515.483
46	300	**338.599**	33	10	4	75	515.761	95	400	500	33	10	**2.958**	100	516.289
47	300	400	33	8	**3.331**	50	515.531	96	400	500	33	10	**3.687**	125	515.188
48	300	400	33	8	4	**62.540**	497.969	97	400	500	33	10	4	**136.671**	512.185
49	300	**473.564**	33	8	4	75	515.155	98	400	**536.193**	33	10	4	150	515.795

Table 7. Continuing

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
99	300	400	33	**8.905**	4	75	510.685	115	400	**593.687**	33	10	4	175	515.519
100	300	**422.150**	33	10	2	50	515.660	116	400	600	33	8	2	**59.322**	502.725
101	300	400	33	10	**2.146**	50	515.673	117	400	600	33	**9.125**	2	75	511.801
102	300	400	33	10	**3.220**	75	515.799	118	400	600	33	8	**2.625**	75	515.954
103	300	400	33	10	4	**94.495**	509.545	119	400	600	33	8	**3.503**	100	516.277
104	300	**422.150**	33	10	4	100	515.660	120	400	600	33	8	4	**115.591**	511.881
105	300	**499.226**	33	10	4	125	515.291	121	400	600	33	**8.337**	4	125	513.058
106	300	**586.164**	33	8	2	50	515.260	122	400	600	33	**9.125**	4	150	511.801
107	300	500	33	**8.871**	2	50	510.596	123	400	600	33	**9.909**	4	175	514.903
108	300	500	33	8	**2.485**	50	515.897	124	400	600	33	10	2	**90.620**	508.820
109	300	500	33	8	**3.720**	75	515.067	125	400	600	33	10	**2.250**	100	515.666
110	300	500	33	8	4	**81.980**	508.222	126	400	600	33	10	**2.814**	125	515.848
111	300	**586.164**	33	8	4	100	515.260	127	400	600	33	10	**3.377**	150	515.863
112	300	500	33	**8.871**	4	100	510.596	128	400	600	33	10	**3.935**	175	515.516
113	300	500	33	**9.988**	4	125	515.197	129	400	600	33	10	4	**178.224**	514.800
114	300	500	33	10	2	**65.068**	499.573								

Table 8. Beam designs under 700.7 kN shear force by the 1D FIL method for Problem-4

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
1	288	555	20	8	**3.303**	50	705.046	19	288	555	40	8	**3.125**	50	704.695
2	288	555	20	8	4	**63.093**	679.873	20	288	555	40	8	4	**66.376**	683.556
3	288	555	20	**8.852**	4	75	696.633	21	288	555	40	**8.622**	4	75	698.673
4	288	555	20	10	**2.125**	50	705.577	22	288	555	**42.051**	10	2	50	704.844
5	288	555	20	10	**3.180**	75	704.022	23	288	555	40	10	**2.008**	50	704.458
6	288	555	20	10	4	**95.395**	697.178	24	288	555	40	10	**3.017**	75	705.311
7	288	555	25	8	**3.248**	50	704.219	25	288	555	40	10	4	**99.683**	703.844
8	288	555	25	8	4	**64.103**	679.926	26	288	555	**42.051**	10	4	100	704.844
9	288	555	25	**8.783**	4	75	696.727	27	288	555	50	**9.908**	2	50	704.715
10	288	555	25	10	**2.086**	50	703.636	28	288	555	50	8	**3.054**	50	704.707
11	288	555	25	10	**3.132**	75	704.121	29	288	555	50	8	4	**67.688**	685.948
12	288	555	25	10	4	**96.757**	697.959	30	288	555	50	**8.527**	4	75	699.444
13	288	555	30	8	**3.204**	50	704.395	31	288	555	50	**9.908**	4	100	704.715
14	288	555	30	8	4	**64.920**	681.087	32	288	555	50	10	2	**51.227**	701.252
15	288	555	30	**8.727**	4	75	697.635	33	288	555	50	10	**2.948**	75	705.061
16	288	555	30	10	**2.059**	50	704.048	34	288	555	50	10	**3.935**	100	705.724
17	288	555	30	10	**3.093**	75	704.965	35	288	555	50	10	4	**102.056**	702.812
18	288	555	30	10	4	**97.787**	700.106								

Table 9. Beam designs under 450 kN shear force by the *1D FIL* method for Problem-5

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
1	275	412	28	**9.327**	2	50	435.440	6	275	412	28	10	2	**58.991**	425.147
2	275	412	28	8	**2.735**	50	439.168	7	275	412	28	10	**2.640**	75	438.881
3	275	412	28	8	4	**73.751**	436.069	8	275	412	28	10	**3.521**	100	439.007
4	275	412	28	**8.090**	4	75	438.052	9	275	412	28	10	4	**114.992**	434.506
5	275	412	28	**9.327**	4	100	435.440								

Table 10. Beam designs under 355.9 kN shear force by the 1D FIL method for Problem-6

No	b (mm)	h (mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)	No	b (mm)	h mm)	f_{ck} (MPa)	ϕ_T (mm)	n	s (mm)	$V_r^{Conv.}$ (kN)
1	200	600	25	8	2	**72.506**	351.520	4	300	600	25	**9.402**	4	225	353.479
2	**240.711**	600	25	8	2	75	355.921	5	300	600	25	**9.960**	4	250	355.623
3	200	600	25	**8.180**	2	75	354.465	6	300	600	25	10	2	**126.07**	355.474
7	200	600	25	8	**2.100**	75	355.821	35	300	600	25	10	**2.385**	150	356.057
8	200	600	25	**9.441**	2	100	353.413	36	300	600	25	10	**2.782**	175	356.028
9	200	600	25	8	**2.798**	100	355.625	37	300	600	25	10	**3.178**	200	355.869
10	200	600	25	8	**3.500**	125	355.764	38	300	600	25	10	**3.574**	225	355.770
11	200	600	25	8	4	**143.754**	354.002	39	300	600	25	10	**3.971**	250	355.814
12	**240.711**	600	25	8	4	150	355.921	40	300	600	25	10	4	**251.961**	355.654
13	200	600	25	**8.180**	4	150	354.465	41	363.583	600	25	10	4	275	355.891
14	200	600	25	**8.814**	4	175	352.644	42	400	600	25	8	2	**94.706**	352.995
15	200	600	25	**9.441**	4	200	353.413	43	400	600	25	**8.253**	2	100	354.571
16	200	600	25	10	2	**112.467**	352.333	44	400	600	25	8	**2.141**	100	356.000
17	**294.592**	600	25	10	2	125	355.817	45	400	600	25	**9.222**	2	125	353.701
18	200	600	25	10	**2.251**	125	355.911	46	400	600	25	8	**2.676**	125	355.964
19	200	600	25	10	**2.701**	150	355.882	47	400	600	25	8	**3.215**	150	356.252

Tablo 10. Continuing

20	200	600	25	10	**3.152**	175	*356.031*	48	400	600	25	8	**3.741**	175	*355.643*
21	200	600	25	10	**3.601**	200	*355.907*	49	400	600	25	8	4	**187.865**	*354.782*
22	200	600	25	10	4	**222.742**	*355.134*	50	400	600	25	**8.253**	4	200	*354.571*
23	**209.443**	600	25	10	4	225	*355.447*	51	400	600	25	**8.732**	4	225	*353.167*
24	**294.592**	600	25	10	4	250	*355.817*	52	400	600	25	**9.222**	4	250	*353.701*
25	300	600	25	8	2	**82.317**	*351.695*	53	400	600	25	**9.702**	4	275	*354.754*
26	300	600	25	**8.847**	2	100	*352.819*	54	400	600	25	10	2	**145.853**	*354.886*
27	300	600	25	8	**2.470**	100	*355.839*	55	400	600	25	10	**2.065**	150	*355.795*
28	300	600	25	**9.960**	2	125	*355.623*	56	400	600	25	10	**2.411**	175	*355.966*
29	300	600	25	8	**3.088**	125	*355.908*	57	400	600	25	10	**2.757**	200	*356.055*
30	300	600	25	8	**3.708**	150	*356.029*	58	400	600	25	10	**3.100**	225	*355.926*
31	300	600	25	8	4	**162.853**	*354.426*	59	400	600	25	10	**3.446**	250	*356.056*
32	**355.317**	600	25	8	4	175	*355.693*	60	400	600	25	10	**3.788**	275	*355.885*
33	300	600	25	**8.290**	4	175	*354.068*	61	400	600	25	10	4	**290.921**	*355.478*
34	300	600	25	**8.847**	4	200	*352.819*								

Table 11. Beam designs under 643.2 kN shear force by the *1D FIL* method for Problem-7

No	*b* (mm)	*h* (mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)	*No*	*b* (mm)	*h* mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)
1	200	**554.3743**	20	10	2	50	*643.485*	21	300	600	20	10	2	**60.16177**	*622.924*
2	200	**548.5729**	25	10	2	50	*642.688*	22	300	600	25	10	2	**61.58527**	*621.347*
3	200	**544.456**	30	10	2	50	*643.284*	23	300	600	30	10	2	**62.70804**	*621.733*
4	200	**535.747**	40	10	2	50	*642.286*	24	300	600	40	10	2	**64.60139**	*623.982*
5	**299.9139**	500	50	10	2	50	*643.342*	25	300	600	50	10	2	**66.455**	*625.323*
6	200	**529.7235**	50	10	2	50	*643.286*	26	400	**497.7321**	30	10	2	50	*644.037*
7	200	600	20	10	2	**56.735**	*624.781*	27	400	**484.6242**	40	10	2	50	*643.716*
8	200	600	25	10	2	**57.646**	*623.019*	28	400	**473.7396**	50	10	2	50	*643.528*
9	200	600	30	10	2	**58.326**	*623.008*	29	400	**513.4757**	20	10	2	50	*643.287*
10	200	600	40	10	2	**59.799**	*620.955*	30	400	**504.2314**	25	10	2	50	*642.516*
11	200	600	50	10	2	**60.766**	*622.543*	31	400	500	**28.242**	10	2	50	*643.620*
12	300	**499.9762**	50	10	2	50	*643.343*	32	400	500	30	10	2	**50.45898**	*642.462*
13	300	**533.607**	20	10	2	50	*644.079*	33	400	500	40	10	2	**53.19484**	*634.516*
14	300	**525.721**	25	10	2	50	*643.041*	34	400	500	50	10	2	**55.60766**	*629.678*
15	**389.078**	500	30	10	2	50	*643.918*	35	400	600	20	10	2	**63.83655**	*622.572*
16	300	**519.3286**	30	10	2	50	*642.835*	36	400	600	25	10	2	**65.69257**	*622.700*
17	**335.611**	500	40	10	2	50	*643.447*	37	400	600	30	10	2	**67.02938**	*625.906*
18	300	**508.937**	40	10	2	50	*643.234*	38	400	600	40	10	2	**69.72376**	*630.398*
19	300	500	**49.973**	10	2	50	*643.344*	39	400	600	50	10	2	**72.02353**	*634.815*
20	300	500	50	10	2	**50.005**	*643.326*								

Table 12. Beam designs under 337.5 kN shear force by the 1D FIL method for Problem-8

No	*b* (mm)	*h* (mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)	*No*	*b* (mm)	*h* mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)
1	200	**496.340**	50	8	4	130	*336.070*	4	300	**463.088**	40	8	4	130	*336.384*
2	200	**539.042**	20	8	4	130	*336.045*	5	300	**448.934**	50	8	4	130	*336.243*
3	**274.699**	500	25	8	4	130	*336.493*	6	**305.941**	500	20	8	4	130	*336.198*
7	200	**529.803**	25	8	4	130	*336.098*	15	300	**502.012**	20	8	4	130	*336.180*
8	**249.436**	500	30	8	4	130	*336.087*	16	300	500	**20.870**	8	4	130	*336.327*
9	200	**521.482**	30	8	4	130	*335.964*	17	400	**470.188**	20	8	4	130	*336.366*
10	**216.248**	500	40	8	4	130	*336.168*	18	400	**456.372**	25	8	4	130	*336.230*
11	200	**507.912**	40	8	4	130	*336.116*	19	400	**444.788**	30	8	4	130	*336.251*
12	200	500	**46.780**	8	4	130	*336.182*	20	400	**425.544**	40	8	4	130	*336.121*
13	300	**490.596**	25	8	4	130	*336.531*	21	400	**410.467**	50	8	4	130	*335.491*
14	300	**479.882**	30	8	4	130	*336.170*								

Table 13. Beam designs under 867.6 kN shear force by the *1D FIL* method for Problem-9

No	*b* (mm)	*h* (mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)	*No*	*b* (mm)	*h* mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)
1	366	495	41	**9.862**	3	50	*887.313*	2	366	495	41	10	3	**51.85052**	*880.620*

Table 14. Beam designs under 100.8 kN shear force by the 1D FIL method for Problem-10

No	*b* (mm)	*h* (mm)	f_{ck} (MPa)	ϕ_T (mm)	*n*	*s* (mm)	$V_r^{Conv.}$ (kN)
1	220	350	22	**9.210**	2	255	*97.591*

Table 15. Beam designs under 123.4 kN shear force by the *1D FIL* method for Problem-11

No	**b** *(mm)*	**h** *(mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*	**No**	**b** *(mm)*	**h** *mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*
1	200	300	20	8	**3.523**	177	*123.228*	2	200	300	20	10	**2.281**	177	*123.358*

Table 16. Beam designs under 1323.2 kN shear force by the *1D FIL* method for Problem-12

No	**b** *(mm)*	**h** *(mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*	**No**	**b** *(mm)*	**h** *mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*
1	200	**589.718**	25	10	4	50	*1323.322*	23	300	600	40	10	**3.732**	50	*1323.165*
2	200	**586.339**	30	10	4	50	*1321.461*	24	300	600	40	10	4	**55.020**	*1292.099*
3	200	**583.267**	40	10	4	50	*1325.133*	25	300	600	50	10	**3.688**	50	*1324.180*
4	200	**578.354**	50	10	4	50	*1322.821*	26	300	600	50	10	4	**55.872**	*1289.515*
5	**233.256**	600	20	10	4	50	*1351.084*	27	400	**569.074**	20	10	4	50	*1323.893*
6	200	600	**22.456**	10	4	50	*1344.625*	28	400	**563.283**	25	10	4	50	*1322.701*
7	200	600	25	10	**3.922**	50	*1323.292*	29	400	**556.534**	30	10	4	50	*1317.492*
8	200	600	25	10	4	**51.456**	*1311.942*	30	400	**550.872**	40	10	4	50	*1323.922*
9	200	600	30	10	**3.897**	50	*1321.523*	31	400	**534.891**	50	10	4	50	*1300.202*
10	200	600	30	10	4	**51.937**	*1306.863*	32	400	600	20	10	**3.757**	50	*1323.914*
11	200	600	40	10	**3.871**	50	*1324.958*	33	400	600	20	10	4	**54.570**	*1294.333*
12	200	600	40	10	4	**52.407**	*1307.296*	34	400	600	25	10	**3.709**	50	*1322.570*
13	200	600	50	10	**3.834**	50	*1322.937*	35	400	600	25	10	4	**55.446**	*1290.097*
14	200	600	50	10	4	**53.119**	*1301.029*	36	400	600	30	10	**3.654**	50	*1317.954*
15	300	**580.426**	20	10	4	50	*1323.189*	37	400	600	30	10	4	**56.495**	*1281.591*
16	300	**575.716**	25	10	4	50	*1321.870*	38	400	600	40	10	**3.601**	50	*1324.164*
17	300	**572.471**	30	10	4	50	*1323.047*	39	300	600	20	10	**3.850**	50	*1323.306*
18	300	**566.059**	40	10	4	50	*1323.220*	40	300	600	20	10	4	**52.829**	*1302.730*
19	300	**560.855**	50	10	4	50	*1324.177*	41	300	600	25	10	**3.812**	50	*1321.837*
20	300	600	25	10	4	**53.514**	*1297.942*	42	400	600	40	10	4	**57.556**	*1283.642*
21	300	600	30	10	**3.785**	50	*1322.977*	43	400	600	50	10	**3.553**	50	*1328.891*
22	300	600	30	10	4	**54.006**	*1296.722*	44	400	600	50	10	4	**58.702**	*1279.840*

Table 17. Beam designs under 70.0 kN shear force by the 1D FIL method for Problem-13

No	**b** *(mm)*	**h** *(mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*	**No**	**b** *(mm)*	**h** *mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*
1	**268.090**	300	20	8	2	300	*69.643*	5	**215.968**	300	30	8	2	300	*69.137*
2	200	**340.691**	20	8	2	300	*69.432*	6	200	**310.825**	30	8	2	300	*69.142*
3	**239.636**	300	25	8	2	300	*69.619*	7	200	300	**36.154**	8	2	300	*69.757*
4	200	**324.576**	25	8	2	300	*69.357*								

Table 18. Beam designs under 1100 kN shear force by the 1D FIL method for Problem-14

No	**b** *(mm)*	**h** *(mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*	**No**	**b** *(mm)*	**h** *mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*
1	**330.920**	600	50	10	4	70	1073.038	3	400	600	50	**9.777**	4	70	1066.150
2	400	**581.165**	50	10	4	70	1068.773	4	400	600	50	10	**3.839**	70	1069.394

Table 19. Beam designs under 90 kN shear force by the 1D FIL method for Problem-15

No	**b** *(mm)*	**h** *(mm)*	**f_{ck}** *(MPa)*	**ϕ_T** *(mm)*	**n**	*s* *(mm)*	**$V_r^{Conv.}$** *(kN)*
1	205	302	27.67339	10	2	280	87.291

As can be seen from all of these design tables, only designs for the targeted output value were performed by the *1D FIL* method. The *1D FIL* method does not produce designs that are very close to the targeted output value, even if they are safe. To put it more clearly, according to the *1D FIL* method, for example, for targeted shear strength of 500 kN, a design with a shear force of 501 kN is not a result. Although this seems to be a disadvantage of the *1D FIL* method, it is foreseen that the *1D FIL* method, which only gives outputs with *Demand/Capacity=1* as a result, can be used in sensitive optimization studies.

Taking into account the errors in the *1D FIL* results arising from the data of the FL model, using the equation given in Equation 22 instead of Equation 4 in the *1D FIL* method will allow obtaining almost all safe designs.

$$O_s < kxO_D < O_B \tag{22}$$

The k parameter in Equation 22 can be calculated by Equation 23 by considering the maximum error (e_{max}) in the designs performed by the 1D FIL method in this study. It is appropriate to take k=1+0.05533≅1.06 for the beam designs discussed in this study.

$$k \geq 1 + \%e_{max}$$

8. Conclusions and recommendations

Some of the conclusions obtained from this study are given below.

- In this study, an FL model was developed for the estimation of shear strength capacities of RC beams with limited ductility and its validity was proven by testing it with a very low amount of error (e_{max}=*3.452%*).
- For the first time, a real design has been carried out for RC beams with limited ductility subjected to shear with an AI method.
- By applying the 1D FIL method to the developed FL model without making any changes in the data of this model, a total of 521 designs of 15 different RC beams with limited ductility were successfully carried out. The maximum absolute error in the designs was determined as 5.523%.
- By the 1D FIL method, it is possible to perform a general design as in Problem 1, as well as to design for certain/mandatory/constant values of the problem parameters(see Problem 2-15).
- The 1D FIL method can also be used as a very sensitive testing tool for FL models developed.
- The values of the problem parameters obtained for the designs with the 1D FIL method are within the data ranges of the variables and outputs of the FL model.
- By the 1D FIL method, the designs with *Demand/Capacity*=1 can be obtained at once. In this respect, it is foreseen that it will be a useful method for performing optimum designs. Additionally, if desired, it is possible to perform designs in different Demand/Capacity ratios with the 1D FIL method.

A more general strength estimation tool can be created by expanding the data limits of the variable parameters in the FL model developed in this study. However, by narrowing these data limits, a strength estimation tool can be created for more specific problems. These strength estimation tools can be added to the analysis programs used in civil engineering as an AI module and can be used in designs with the 1d FIL method.

In this study, before using the designs obtained by the 1D FIL method directly, their compliance with other design conditions in the regulations, if any, should be checked. Finally, it is foreseen that the 1D FIL method along with a sensitively constituted FL model can be used effectively for control, optimization, design, robotic, autonomous vehicles, etc. problems in many other scientific fields.

Author contribution

Research design, fuzzy logic calculations, fuzzy inverse logic calculations, computer code writing, data analysis, article writing and final approval.

Declaration of ethical code

The author of this article declares that the materials and methods used in this study do not require ethical committee approval and/or legal-specific permission.

Conflicts of interest

The author declares that there is no conflict of interest.

References

Allali, S. A., Abed, M., & Mebarki, A. (2018). Post-earthquake assessment of buildings damage using fuzzy logic, *Engineering Structures, 166*, 117-127. https://doi.org/10.1016/j.engstruct.2018.03.055

Akintunde, O. P. (2021). Fuzzy Logic design approach for a singly reinforced concrete beam, *Journal of Civil Engineering Research & Technology*. SRC/JCERT-111, 3. https://doi.org/10.47363/JCERT/2021(3)111.

Amani, J., & Moeini, R. (2012). Prediction of shear strength of reinforced concrete beams using adaptive neuro-fuzzy inference system and artificial neural network, *Scientia Iranica*, *19*(2), 242-248. https://doi.org/10.1016/j.scient.2012.02.009

Cao, Y., Zandi, Y., Rahimi, A., Petković, D., Denić, N., Stojanović, J., ... & Assilzadeh, H. (2021, December). Evaluation and monitoring of impact resistance of fiber reinforced concrete by adaptive neuro fuzzy algorithm, *Structures, 34*. 3750-3756. https://doi.org/10.1016/j.istruc.2021.09.072

Cao, Y., Fan, Q., Azar, S. M., Alyousef, R., Yousif, S. T., Wakil, K., ... & Alaskar, A. (2020). Computational parameter identification of strongest influence on the shear resistance of reinforced concrete beams by fiber reinforcement polymer, *Structures*, *27*, 118-127. https://doi.org/10.1016/j.istruc.2020.05.031

Chao, C. J., & Cheng, F. P. (1998). Fuzzy pattern recognition model for diagnosing cracks in RC structures. *Journal of computing in civil engineering*, *12*(2), 111-119.

Choi, S. K., Tareen, N., Kim, J., Park, S., & Park, I. (2018). Real-time strength monitoring for concrete structures using EMI technique incorporating with fuzzy logic, *Applied Sciences*, 8(1), 75. https://doi.org/10.3390/app8010075

Cukaric, A., Camagic, I., Dutina, V., Milkic, Z., & Jovic, S. (2019). Parameters ranking based on influence on dynamical strength of ultra-high performance concrete by neuro fuzzy logic, *Struct Concr*, *433*, 1-7. https://doi.org/10.1002/suco.201900433

De Iuliis, M., Kammouh, O., Cimellaro, G. P., & Tesfamariam, S. (2019). Downtime estimation of building structures using fuzzy logic, *International journal of disaster risk reduction*, *34*, 196-208. https://doi.org/10.1016/j.ijdrr.2018.11.017

Doğangün, Adem, *Betonarme yapıların hesap ve tasarımı(Turkish)*, Birsen yayınevi 17th edition, 2021, İstanbul/Turkey.

Doran, B., Yetilmezsoy, K., & Murtazaoglu, S. (2015). Application of fuzzy logic approach in predicting the lateral confinement coefficient for RC columns wrapped with CFRP, *Engineering Structures*, *88*, 74-91. https://doi.org/10.1016/j.engstruct.2015.01.039

Elbeltagi, E., Hosny, O. A., Elhakeem, A., Abd-Elrazek, M. E., & Abdullah, A. (2011). Selection of slab formwork system using fuzzy logic, *Construction Management and Economics*, *29*(7), 659-670. https://doi.org/10.1080/01446193.2011.590144

Elenas, A., Vrochidou, E., Alvanitopoulos, P., & Andreadis, I. (2013). Classification of seismic damages in buildings using fuzzy logic procedures, *In Computational Methods in Stochastic Dynamics*. 335-344. https://doi.org/10.1007/978-94-007-5134-7_20

Garzón-Roca, J., Marco, C. O., & Adam, J. M. (2013). Compressive strength of masonry made of clay bricks and cement mortar: Estimation based on Neural Networks and Fuzzy Logic, *Engineering Structures*, *48*, 21-27. https://doi.org/10.1016/j.engstruct.2012.09.029

Golafshani, E. M., Rahai, A., Sebt, M. H., & Akbarpour, H. (2012). Prediction of bond strength of spliced steel bars in concrete using artificial neural network and fuzzy logic, *Construction and building materials, 36*, 411-418. https://doi.org/10.1016/j.conbuildmat.2012.04.046

Govardhan, P., Kalapatapu, P., & Pasupuleti, V. D. K. (2021). Identification of Multiple Cracks on Beam using Fuzzy Logic, 2021 *International Conference on Emerging Techniques in Computational Intelligence*, 165-169. https://doi.org/10.1109/ICETCI51973.2021.9574059

Harirchian, E., & Lahmer, T. (2020). Developing a hierarchical type-2 fuzzy logic model to improve rapid evaluation of earthquake hazard safety of existing buildings, *Structures 28,* 1384-1399. https://doi.org/10.1016/j.istruc.2020.09.048

Khoshnoudian, F., & Molavi-Tabrizi, A. (2012). Responses of isolated building with MR Dampers and Fuzzy Logic, *International Journal of Civil Engineering*, *10*(3).

Mamdani, E. H. and Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies*, *7*(1), 1-13. https://doi.org/10.1016/S0020-7373(75)80002-2

Mamdani, E. H. (1976). Advances in the linguistic synthesis of fuzzy controllers, *International Journal of Man-Machine Studies,* 8(6), 669-678. https://doi.org/10.1016/S0020-7373(76)80028-4.

Mirrashid, M., & Naderpour, H. (2020). Recent trends in prediction of concrete elements behavior using soft computing (2010–2020), *Archives of Computational Methods in Engineering*, *4*,1-21. https://doi.org/10.1007/s11831-020-09500-7

Naderpour, H., & Alavi, S. A. (2017). A proposed model to estimate shear contribution of FRP in strengthened RC beams in terms of Adaptive Neuro-Fuzzy Inference System, *Composite Structures, 170,* 215-227. https://doi.org/10.1016/j.compstruct.2017.03.028

Naderpour, H., Nagai, K., Haji, M., & Mirrashid, M. (2019). Adaptive neuro-fuzzy inference modelling and sensitivity analysis for capacity estimation of fiber reinforced polymer-strengthened circular reinforced concrete columns, *Expert Systems*, *36*(4), e12410. https://doi.org/10.1111/exsy.12410

Ozkul, S., Ayoub, A., & Altunkaynak, A. (2014). Fuzzy-logic based inelastic displacement ratios of degrading RC structures, *Engineering structures*, 75, 590-603. https://doi.org/10.1016/j.engstruct.2014.06.030

Öztekin, E. (2021). Fuzzy inverse logic: part-1. Introduction and bases. *Gümüşhane Üniversitesi Fen Bilimleri Dergisi* , *11* (3) , 675-691 . https://doi.org/10.17714/gumusfenbil.894674

Öztekin, E. (2021). Fuzzy inverse logic: part-2. Validation and evaluation of the method. *Gümüşhane Üniversitesi Fen Bilimleri Dergisi* , 11 (3) , 768-791 . https://doi.org/10.17714/gumusfenbil.894879

Sung, Y. C., & Su, C. K. (2010). Fuzzy genetic optimization on performance-based seismic design of reinforced concrete bridge piers with single-column type, *Optimization and Engineering*, *11*(3), 471-496. https://doi.org/10.1007/s11081-009-9092-4

Şen, Z. (2010). Rapid visual earthquake hazard evaluation of existing buildings by fuzzy logic modeling, *Expert systems with Applications*, *37*(8), 5653-5660. https://doi.org/10.1016/j.eswa.2010.02.046

Şen, Z. (2011). Supervised fuzzy logic modeling for building earthquake hazard assessment, *Expert systems with applications*, *38*(12), 14564-14573. https://doi.org/10.1016/j.eswa.2011.05.026

TBEC. *Turkish Building Earthquake Code*; T.C. Resmi Gazete: Ankara, Turkey, 2018.

Tekeli, H., Korkmaz, K. A., Demir, F., & Carhoglu, A. I. (2014). Comparison of critical column buckling load in regression, fuzzy logic and ANN based estimations, *Journal of Intelligent & Fuzzy Systems, 26*(3), 1077-1087. https://doi.org/10.3233/IFS-120701

TS 500, Requirements for design and construction of reinforced concrete structures, Turkish Standarts, Institute: Ankara, Türkiye, 2000.

Ud Darain, K. M., Jumaat, M. Z., Hossain, M. A., Hosen, M. A., Obaydullah, M., Huda, M. N., & Hossain, I. (2015). Automated serviceability prediction of NSM strengthened structure using a fuzzy logic expert system, *Expert systems with applications*, *42*(1), 376-389. https://doi.org/10.1016/j.eswa.2014.07.058

Uzunoğlu, M., & Kap, T. (2012). Prediction of concrete compressive strength in buildings that would be reinforced by fuzzy logic, *International Journal of Physical Sciences*, *7*(31), 5193-5201. https://doi.org/10.5897/IJPS12.155

Zabihi-Samani, M., & Ghanooni-Bagha, M. (2019). Optimal semi-active structural control with a wavelet-based cuckoo-search fuzzy logic controller, *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, *43*(4), 619-634. https://doi.org/10.1007/s40996-018-0206-0

Zadeh, L. A. (1965), Fuzzy Sets, *Information and control*, *8*(3), 338-353. https://doi.org/10.1016/S0019-9958(65)90241-X

Zadeh, L. A. (1973). Outline of a new approach to the analysis of complex systems and decision processes, *IEEE Transactions on systems, Man and Cybernetics*, (1), 28-44. https://doi.org/10.1109/TSMC.1973.5408575

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning-III, *Information Siences*, *9*(1), 43-80. https://doi.org/10.1016/0020-0255(75)90036-5